STRATIGRAPHY OF THE UPPER CRUST OF MARS. A. S. McEwen[1], [1] Lunar and Planetary Lab, University of Arizona, Tucson, AZ 85721 (mcewen@lpl.arizona.edu).

Introduction

The stratigraphy of the upper crust of Mars is a record of the geologic history over the past ~4 Gyr. MGS has just begun to provide a deluge of new information on the stratigraphy from high-resolution MOC images. An attempt at this time to synthesize and review the new data in terms of the geologic history of Mars is premature and very likely to be rendered obsolete within the next few months. Such an attempt follows anyhow, but take it with a grain of evaporite. The main purpose of the talk will be to show a set of spectacular new images of the crustal stratigraphy.

MOC has shown that layering is very common in the upper crust of Mars (Edgett and Malin, 1999). The crust is exposed to significant depths (up to 10 km) only in Valles Marineris, and almost all of the wall rocks, where exposed, are layered (McEwen et al., 1999). The appearance of the layering varies from place to place due to a combination of (1) degree and style of eolian burial or erosion; (2) observation geometry (especially sunangle and resolution); (3) modification by tectonics and mass wasting; and (4) differences in the composition and emplacement of the original geologic horizons. Apparent layer thickness is a strong function of spatial resolution. Many units that appear homogeneous at lower resolution are seen to be more finely layered at higher resolution. Even units that appear homogeneous in early MOC images (~5 m/pixel) may be surprisingly different at the 1.4 m/pixel resolution available (planetwide) during the mapping mission. But the stratigraphy or slope modification may vary laterally and differences in illumination angle could be important as well. These issues have not yet been sorted out because MOC images acquired to date are widely spaced and there has been little time to analyze the data.

The layers appear to be mostly horizontal, with a few exceptions, but coanalysis with MOLA elevation data is needed. If we assume that the layers were originally horizontal, then sloping layers can be mapped out to provide a constraint on tectonic deformations.

There is little direct compositional information on the crustal layers. It seems clear that the surface of Mars is dominated by volcanic lithologies, from near-IR and thermal emission spectroscopy, in-situ data from landers, and from the SNC meteorites (see various abstracts in this volume). However, the great majority of the surface is covered by eolian materials that could hide the composition of underlying units. It appears from MOC images that the underlying units are well exposed only over steep slopes and over areas up to a few meters wide.

A variety of stratigraphic units are thought to exist in the crust of Mars (Tanaka et al., 1994). Below I discuss three plausible hypotheses for the layering of Mars.

Heavily Cratered Highland Units

These units are thought to consist of impact breccias and fractured bedrock (perhaps uplifted in basin massifs or central peaks). On the Moon such units are only very crudely layered. There is relatively fine layering underlying heavily cratered (Noachian) units in many areas of Mars, best exposed in eastern Valles Marineris and the chaotic terrain. There are many other areas where no layering is apparent, even where there is significant topographic relief, but the slopes are relatively gentle (up to ~20°) and may be covered by regolith. Where the stratigraphy has been exposed due to relatively recent tectonism or collapse, layering is common. But it is apparent that these steep slopes do not provide an unbiased sampling of the crust. In eastern Valles Marineris and the chaotic terrain collapse has clearly been localized by large impacts, so that the heavily brecciated crater interior has collapsed and only the intercrater plains are left standing and exposed in the steep slopes. The intercrater plains probably formed from a combination of impact ejecta blankets, volcanic flows, and locally-derived sedimentary deposits.

Flood Lavas

The ridged plains covering ~22% of Mars' surface are usually interpreted as flood lavas (Tanaka et al., 1994), and McEwen et al. (1999) proposed that the deep layering in the outer walls of Valles Marineris could all be primarily due to flood lavas. Flood lava eruption and modification processes on Mars may be very different from those on Earth, with important effects on the upper crustal layering.

Terrestrial flood lavas are largely emplaced via prolonged eruptions in which initially thin flows are inflated to tens of meters thickness under the crust (Self et al., 1997). The resulting flow lobes consist of (1) highly vesicular upper crust (40-50% of flow thickness), (2) lava core, and (3) thin glassy basal zone. The upper crust weathers out into slopes while the dense lava forms cliffs. The lava cliffs are darker than the slopes--covered by soil and vegetation. The combination of alternate bright-dark banding, stepped topography, layer thicknesses of 5-50 m, and irregularities at the scale of meters is distinctive in terrestrial flood basalts and in Valles Marineris outer walls. However, except for the upper cap rock, the walls of Valles Marineris do not exhibit the physical stability expected of intact basalt flows (Clow and Moore, 1988).

The surfaces of inflated lavas have a distinctive mottled appearance. But in SE Elysium, Amazonis, and Tharsis regions of Mars, the recent flood lavas with well-preserved surface morphologies appear to have been emplaced rapidly, in channels, and show only a little bit of evidence for inflated lobes near the margins (Keszthelyi et al., 1999). Maybe they are emplaced via a combination of channels and inflation, like the Laki flow in Iceland. Given the very low slopes, the volumes needed for each eruption episode are enormous. This may be why the northern plains are so flat, to first order, although there must be eolian and fluvial deposits over much of the surface.

On Earth, the whole eruption field (several km thick) is emplaced in geologically short time spans (up to ~25 Myr) (Ernst and Buchan, 1997). From crater counts in SE Elysium and Amazonis Planitiae it is clear that adjacent lavas have widely different ages, ranging from perhaps 1-1000

Myr (Hartmann et al., 1999). Uncertainties in the current cratering rate at Mars could shift around the absolute age estimates, but the spread of ages seems secure. Some of these young crater ages may be misleading, as we can see that the Medusae Fossae Formation (MFF) is being deflated off of the tops of the lava in places. There must be a close genetic relation between the flood lavas and the MFF--probably the MFF consists of tephra.

Perhaps both of these differences from terrestrial eruptions (rapid emplacement of voluminous flows, and long repose time between eruptive episodes) can be explained by the thicker lithosphere of Mars. Only voluminous batches of magma make it to the surface, but in episodes that are widely spaced in time. How this might relate to mantle plume dynamics is a puzzle.

Were the Valles Marineris flood lavas (assuming for now that this is indeed the layer composition) also emplaced in widely-spaced voluminous episodes? If so, then there was ample time for impact gardening and other modification processes of each flow prior to burial by the next flow. Hartmann (1999) showed that surfaces as young as 100 Myr reach crater saturation equilibrium at $D < 60$ m. Lunar mare measurements indicate that the regolith thickness, h, is related to saturation equilibrium diameter, D_{eq} by $h = D_{eq}/25$ (Oberbeck and Quaide, 1969; see Table 10.1 in Melosh, 1984). There will also be fracturing of the underlying rock to depths many times the crater diameter (Melosh, 1989, p. 72). The regolith formation and bedrock fracturing would be accelerated in the late Noachian, during the tail end of heavy bombardment, assuming a lunar-like cratering chronology. Could this explain the instability of the deep Valles Marineris wall rocks?

Lets estimate that there are >200 layers in Valles Marineris, each ~25 m thick, and an average repose of ~1 Myr between layers. Hence, a 5-km thick section is deposited in ~200 Myr. Assume that the late Noachian cratering rate is 10x the current rate (a reasonable assumption based on the lunar chronology). Crater saturation equilibrium at $D < 16$ m is reached in 1 Myr (or 10 Myr at the current rate--Hartmann, 1999). Hence, a regolith $16/25 = 0.6$ m thick should form, and the entire flow will be fractured. Certainly the strength of a stack of fractured flows alternating with regolith layers will be significantly less than that of intact flows. In the analysis of Clow and Moore (1988), fractured basalt has precisely the cohesion and internal friction angle needed to explain the slopes in Ius and Tithonium Chasmata (see Fig. 10 of Lucchitta et al., 1992). Tectonism and incipient collapse must have further fractured and weakened the wall rocks. Another possibility is that a wetter climate in the late Noachian caused erosion and sedimentation, contributing to unconsolidated horizons.

The next question to consider is why does the uppermost section (~400 meters thick) of VM form a steep cliff in most places? This cap rock was largely emplaced in the early Hesperian, after the tail-off in heavy bombardment, but the surface has nevertheless been exposed to something like the current cratering rate for ~3 Gyr (Tanaka et al., 1992). Crater equilibrium saturation should occur at $D < 350$ m, so there should be a regolith ~14 m thick, much less than the cliff thickness. The entire section should be fractured, but apparently this in insufficient to preclude steep cliffs up to 400 m high. A change in climate and weathering across the Noachian-Hesperian boundary could also contribute to the change in wall rock competency. Another possibility is that the flows were emplaced as thicker units, from more voluminous flows as the lithosphere thickened.

If the deep VM flows were emplaced over 200 Myr in the late Noachian, why do the layers not appear more disrupted in places by large impacts? Because these areas have considerably less strength and collapse into the talus slopes.

Fluvial Sedimentary Deposits

The layering on Mars is coarser than typical thick sedimentary sections on Earth, such as in the Grand Canyon of Arizona. If sedimentary, they must have been emplaced in more energetic environments than that provided by deep oceans. A scenario with flood deposits on dry land or shallow water and impact gardening might be plausible. This hypothesis faces two major difficulties. The first is that such enormous quantities of sediment must be eroded from somewhere, and the fact that any ancient highlands are preserved on Mars is difficult to reconcile with this hypothesis. A second major difficulty is how to explain the current high topography of Valles Marineris, which is near the top of a bulge 10 km above datum. Permanent structural uplift in the absence of plate tectonics is difficult to explain, but can be accomplished over mantle plumes with voluminous magmatism (Phillips et al., 1990). Mantle plumes cause voluminous flood volcanism, so the flood lava interpretation of the layering seems most straightforward. A fluvial sedimentary hypothesis would have to be more complex, with the region first being a deep basin to collect a thick stack of sediments, then uplifted ~20 km by a mantle plume and voluminous magmatic intrusions but relatively little extrusive volcanism.

Conclusions

Rather than speculate endlessly, we need (1) several years to begin to analyze the data from MGS, and (2) future missions that can return compositional information at the scale of meters.

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